

## ULTRASONIC FILL LEVEL DEVICE AND METHOD

### FIELD OF THE INVENTION

The present invention relates generally to the field of liquid level monitoring and  
5 more particularly relates to systems and methods for use in ultrasonically monitoring the  
fill level of a liquid storage container.

### BACKGROUND

There is a widespread need to monitor the fill level of liquid containing  
10 vessels, and there are a variety of ultrasonic level monitors adapted for this purpose.  
However, many ultrasonic level monitors are invasive, requiring placement of some  
hardware in contact with the liquid inside the tank and requiring a connection to that  
hardware which breeches the tank. Others merely provide crude or limited  
information about the fill level, for example by simply determining whether a  
15 particular location inside the tank is wet or dry. Still others require hardware placed at  
more than one location, adding to equipment cost. The ultrasonic monitoring  
techniques currently available thus fail to provide a reliable, accurate, and non-  
invasive sensor that is easily installed at a single point on the exterior of the storage  
tank. More clearly, there is a need for a non-invasive, self-correcting, ultrasonic liquid  
20 level monitor (ULLM) that is inexpensive and can be easily installed, maintained and  
operated. In one form, the present invention meets this need. Other forms of the

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invention provide additional benefits and advantages in a novel and unobvious manner.

## SUMMARY

The present invention relates generally to systems and methods for ultrasonically determining the liquid fill level of a container. While the actual nature of the invention covered herein can only be determined with reference to the claims appended hereto, certain forms of the invention that are characteristic of the embodiments disclosed herein are described briefly as follows.

In one form of the present invention, a system for determining the liquid fill level of a container is comprised of one or more ultrasound transducers and a processing device. The transducers are acoustically associated with a sidewall of a container and are positioned to interrogate the liquid with ultrasound and receive responses. A first received response corresponds to ultrasound reflected from an opposite sidewall along a generally horizontal acoustic path through the liquid, and a second received response corresponds to ultrasound reflected from a “corner” along a generally inclined path through the liquid, wherein a “corner” refers to the intersection between the liquid surface and a sidewall of the container. The processing device calculates time-of-flights and determines height of the liquid surface relative to the location of the transducers. The transducers can include a multi-element transducer having a plurality of transducer elements positioned in differing angular orientations in a common housing.

In another form a method for determining the level of the contents in a container comprises interrogating a container with ultrasound with one or more ultrasonic

transducers in acoustic contact with a sidewall of the container at a transducer location;  
receiving a first response corresponding to ultrasound reflected from an opposite sidewall  
along an acoustic path that is substantially independent of the height of the surface;  
receiving a second response corresponding to ultrasound reflected from an intersection  
5 between the upper surface and a sidewall of the container; and determining a relative  
height of the upper surface from the first and second responses.

It is one object of the present invention to provide improved systems and methods  
for use in non-invasively determining the liquid fill level of containers.

Further objects, features, advantages, benefits, and further aspects of the present  
10 invention will become apparent from the drawings and description contained herein.

## BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is a schematic illustration of a fill level monitoring system.

FIG. 2 is a schematic illustration of additional features of the FIG. 1 system.

FIG. 3 is a schematic illustration of an ultrasonic wavefront originating from the  
5 interrogation device and reflecting from the corner and the opposite wall in the FIG. 1  
system.

FIG. 4 is an illustration of the divergence of ultrasound directed toward the corner  
of the FIG. 1 system.

FIG. 5 is a schematic illustration of a divergent ultrasound beam inside a  
10 container that produces a corner-shot reflection after reflection off the opposing sidewall.

FIG. 5a is a schematic illustration of calculation of height accommodating for the  
reflection off the opposing sidewall.

FIG. 6 is an exemplary plot of amplitude at device 30 after delivery of an  
ultrasound burst in the beam as illustrated in FIG. 5 with exploded regions corresponding  
15 to the range of expected times for receipt of the corner shot reflection.

FIG. 7 is a schematic illustration of a divergent ultrasound beam inside a  
container that does not produce a corner-shot reflection because the liquid level is  
between illuminated zones.

FIG. 8 is an exemplary plot of amplitude at device 30 after delivery of an  
20 ultrasound burst in the beam as illustrated in FIG. 7 with exploded regions corresponding  
to the expected times for receipt of the corner shot reflection.

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FIG. 9 is view of container with a plurality of fill level monitoring devices secured to its exterior.

## DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

For the purposes of promoting an understanding of the principles of the invention, reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no  
5 limitation of the scope of the invention is hereby intended. Alterations and further modifications in the illustrated devices, and such further applications of the principles of the invention as illustrated herein are contemplated as would normally occur to one skilled in the art to which the invention relates.

Briefly, in one aspect the present invention provides a system for monitoring the  
10 fill level of a container based on the detection of ultrasound that reflects obliquely from a “corner” of the container and transversely from the far sidewall. This “corner” refers to the intersection of the fill level and a sidewall of the container, and because the fill level is determined by the interface between the fill contents (typically a liquid) and the material above the contents (typically a gas forming a headspace), this “corner” is  
15 actually the three-way intersection of the sidewall, the liquid and the gas. As described more fully below, from a time-of-flight measurement of the “corner-shot” reflection and information about speed of sound in the liquid obtained from the transverse reflection and the dimensions of the container, one can mathematically determine the fill level. One advantage of this system is that all the acoustic measurements, the corner-shot reflection  
20 and the measurement of the speed of sound, can be taken from a single location on the exterior of the container.

Referring to FIG. 1, schematically shown therein is a fluid level monitoring system 20 for ultrasonically determining the level of liquid 24 in container 22. An ultrasonic interrogation device 30 is acoustically coupled to sidewall 25 of container 22 and is operable to produce ultrasound that travels through the liquid 24 along at least two different acoustic paths 32 and 34. The first acoustic path 32 is a transverse path that is generally horizontal and generally perpendicular to the plane of the sidewall 23. The second acoustic path 34 is an oblique path which is inclined through the liquid 24 and which spans between the device 30 and the intersection 27 between the upper liquid surface 28 and sidewall 23. In the illustrated embodiment, container 22 is a cylindrical container, such as a drum, and sidewalls 23, 25 are substantially vertical and concave interior surfaces of the drum.

Surface 28 is conventionally defined as the interface between the liquid 24 and the material 26 above the liquid 24, and it is the relative height of surface 28, and consequently the position of the intersection 27, that indicates the liquid level of interest. While the contents of the container are herein referred to as a liquid, it is to be understood that the liquid 24 can be any fluid or fluid-like material that only partially fills container 22 and supports propagation of longitudinal ultrasonic waves, including liquids, pastes, sludges, and slurries. The material 26 above the liquid 24 is generally a gas but it can be any material, or combination of materials including another liquid, that establishes a ultrasonically reflective interface with liquid 24 and fills the remainder of the container 22. In certain applications, an intervening material, such as another liquid, might



separate the material 26 and the liquid 24 such that a level measured is the interface between the liquid 24 and this intervening material. For example, oil might be provided between the liquid 24 and headspace material 26. In a variation, liquid 24 is stratified and the fill level monitoring device monitors the location of multiple interfaces between the stratified layers by detecting reflections from each of the different corners.

The interrogation device 30 functions as both the transmitter and receiver for the ultrasonic signals that traverse paths 34 and 32. With reference to Fig. 2, the interrogation device 30 includes one or more transducers 36 in acoustic communication with the liquid 24. Device 30 is illustratively represented with three transducers 36a, 36b, 36c contained within a common housing 31. The transducers 36a-36c are each positioned at different orientations for transmitting and receiving ultrasound along the different acoustic paths 32, 34.

Device 30 is electronically connected to computer system 40 which controls the ultrasonic interrogation and processes the received response to determine the relative location of intersection 27, and thus the liquid level of interest. Computer system 40 includes a microprocessor 44 coupled to a pulser 47 and receiver 48 through appropriate analog to digital (A/D) converters. In operation, pulser 47 generates and delivers a short duration stimulus to one of the transducer 36a, 36b, or 36c, and the transducer responds to the stimulus by emitting a pulse of ultrasound into the liquid 24. A suitably short pulse might have a pulse length less than about 2.0 cm in the liquid 24. This ultrasonic pulse propagates through liquid 24, and at least a portion of the energy of the pulse returns to

the transducer having traversed along one or more of paths 32 or 34. The transducer responds to the return energy, producing an output signal that is amplified, digitized and passed to the microprocessor 44 for time-of-flight determination and further processing according to programming instructions contained in memory 46.

5           Device 30 can be configured to produce different types of ultrasonic interrogation. Fig. 3 illustrates a form of interrogation where an interrogation pulse Z is wide (i.e. has a wide angle of divergence or dispersion) or is unidirectional such that it generates return echoes W, Y both from the corner 27 and a spot on opposite wall 23 that is independent of the liquid level. Where the interrogation is such that there are multiple distinct return  
10   signals, the multiple return signals are differentiated by recognizing that the return energy will arrive along inclined path 34 at a later time than for the horizontal path 32 when sidewall 23 is vertical (need to show 23 in Fig 3). Alternatively or in addition, the interrogation can be directional such that the possible return paths for a given pulse are more limited. Fig. 4 illustrates a form of interrogation where an ultrasound pulse V is  
15   directional and has a characteristic divergence  $\alpha$ . Divergence of an ultrasound beam is conventionally defined relative to a point in the far field as the angle of the cone bounding the region where the ultrasonic signal has diminished in intensity by half relative to the peak signal along the transducer centerline. Where the transducers are directional, horizontal transducer 36a is utilized to transmit and receive the pulse along  
20   the horizontal path 32 and inclined transducers 36b and 36c are used to transmit and receive the pulse along the inclined path 34.

The determination of the liquid level is achieved by calculating the times-of-flight for the received return signals. Because the horizontal dimension D of the container 22 is known, the speed of sound in the liquid 24 can be calculated from the time-of-flight for path 32. From this calculated speed of sound, the length of the inclined path 34 can be  
5 calculated based on its determined time-of-flight. The height of the liquid level 28 is then determined by calculating the altitude h of the right triangle having hypotenuse 34a and leg 32a corresponding to the lengths of paths 34 and 32 respectively. Alternatively, if the dimension D is unknown but the absolute level of fill is initially known, the altitude h may also be determined. In still further variations, if the dimension D is unknown but the  
10 relative level of fill is initially known, the relative altitude h may be determined. In one implementation, computer system 40 calculates the liquid level and provides a corresponding indication on display 42. Other implementations include wired or wireless transmission of the liquid level from the computer system 40 to a remote computer (not shown), for example to control the level of contents in the container 22, having the  
15 computer system 40 signal an alarm condition as appropriate, and combinations thereof.

It will be appreciated that this height measurement does not measure the absolute height of the liquid 24 in the container 22, but rather the height of the surface 28 above the location of device 30. However, because the location of device 30 is known, relative to the bottom of the container, one can readily determine the height of the liquid relative  
20 to the base of the container. The use of gradations or external markings on the container 22 can be employed to assist determining the location of the device 30 relative to the

bottom of the container. Such external markings would be particularly useful in the case where device 30 is a handheld device or otherwise moveable and subject to placement at different locations along the side of a single container 22 and/or as between several containers.

5           Of course, in certain expected applications, the location of intersection 27 and thus the precise location of the corner shot reflection (path 34) is not known in advance, but rather is dependent on the fill level to be determined. The present invention takes advantage of the recognition that, for ultrasound propagating in an inclined direction from a fixed location on the side of the container, the portion that reflects from a “corner”  
10 will generate the strongest signal. Excluding the transverse reflection, it will also generate the earliest return signal. Even where this “corner-shot” reflection involves intermediate reflections from one or more of the sidewalls 23, 25 before and after reaching the corner intersection 27 (see Fig. 5), the straight line path will pass through the corner, allowing calculation of the height  $h$  according to the right triangle relationship of  
15 Fig. 1.

          An exemplary ultrasound trace for the corner shot reflection is shown in Fig. 6. The trace of Fig. 6 corresponds to the interrogation depicted schematically in Fig. 5 where a divergent beam 110, originates as a pulse from device 30 and reflects once off the side wall 23 before reaching corner 27. Based on the known orientation and  
20 divergence of the beam 110, the beam 110 can be predicted to propagate substantially between upper 134a and lower 134b bounds. Based on the calculation of the bounds

134a and 164b and the known dimension of the container, the beam 110 is predicted to illuminate a predefined area 112 on the first sidewall 23, and after one reflection, a predefined area 114 on the second side wall 25. A range for the times-of-flight for the return signal from the corner-shot reflections if the liquid level 28 was in these areas 112, 114, are then determined by utilizing an estimate (or measured value) for speed of sound in the liquid. The ranges for these times-of-flight are indicated by the shaded regions of the upper plot of FIG. 6 with exploded plots of each time window provided below.

Because a corner shot occurs after one sidewall reflection in the conditions depicted in Fig. 5, a distinct pulse is present in the second time window. The presence of this intermediate sidewall reflection is readily accounted for in determining the liquid level by doubling the length of the lower leg of the right triangle as depicted in Fig. 5a. By contrast, Fig. 7 illustrates a geometry where the liquid level 28 falls between the illuminated areas 112, 114. Accordingly no corner-shot reflection occurs for the illustrated beam, and the exploded windows of Fig. 8 do not show a discernible return pulse.

The ability to detect the liquid level depends on the relative size and orientation of the sidewall areas that are illuminated by the ultrasound (112 and 114, for example). In one form, large areas of illumination are achieved by interrogating with non-directional ultrasound, such as with a mechanical impactor, or with a beam having a wide angle of dispersion. In another form, large areas of illumination are achieved by utilizing multiple transducers, each having a relatively narrow angle of dispersion. Because the strength of

the return signal depends on the amount of energy reflecting off the corner (or off the sidewall in the case of the horizontal path 32), use of narrow beams can provide more focused energy, for example to penetrate large distances or through highly attenuating material. For example, it is expected that a series of transducers with angular divergence  
5 between 15-35 degrees in the liquid will be useful in a variety of industrial applications.

The device 30 of Fig. 1 includes three transducers 36a-36c each positioned a different angular orientation, but it is to be understood that more or less transducers could be used. The transducers 36a-36c are mounted on one or more wedge pieces 37 of solid material that serve to orient the transducers and acoustically couple them to the sidewall  
10 25 when the housing 30 is placed in position. These transducers 36a-36c can each have the same or different degrees of divergence, and in one form the transducers are operated sequentially to avoid interference. When using multiple transducers, the transducers can be positioned such that they illuminate overlapping areas on the sidewalls of the container, permitting redundant level measurements for liquid levels falling in the  
15 overlapping illuminated areas.

Making a single estimate of fill level at any one point in time has been the focus of the previous discussion. In certain applications, it may be desirable to improve upon the accuracy or precision of this single point estimate of fill level. For example, the actual fill level may be constant but the single point estimate varies significantly due to  
20 measurement error. It is also possible that the amount of material may be constant, but the actual fill level may vary due to changes in air pressure, heating, cooling, or other

conditions. In cases like these, improved estimates of the true fill level may be calculated by a statistical aggregation of a series of single point level estimates. For example, more recent single point estimates, or those having a higher signal to noise ratio, may be weighted heavier in a weighted mean estimate of fill level. Any useful method for  
5 applying the weights to the single point estimates can be employed. One approach to assigning weights and making the composite (weighted mean) estimate is to utilize Kalman filtering. (R.G. Brown and P.Y.C. Hwang; "An Introduction to Random Signals and Applied Kalman Filtering" John Wiley and Sons, Inc. New York, NY, 1996). A suitable example of the construction of a composite fill level estimate from a series of fill  
10 level estimates is described in Whitney, P. et al. "Screening the Hanford Tanks for Trapped Gas" *Environmentrics* 2002; 13(5/6)411-428, which describes the use of Kalman filtering to correct for temporal variation in fill level estimates attributable to atmospheric effects.

Additional accuracy and redundancy can be achieved by providing multiple devices  
15 30 on a single container. Turning now to Fig. 9, a first strap 200 secures a plurality of devices 30 to the outside of container 22. A second strap 210 secures a second plurality of devices 30 to the outside of container 22 at a position below the first strap. All of the devices 30 are coupled to a common computer (not shown) which controls the orderly interrogation of the liquid level and collects and processes the data. The straps 200 and  
20 210 serve to secure the devices 30 to the exterior of the container 22 and apply pressure as required to form good acoustic communication. The devices 30 can be removed and

secured to other containers 22 if the need arises. Alternatively, if mobility is not a concern, the devices 30 can be permanently mounted to the container 30.

In some applications, the liquid properties or composition changes over time, resulting in changes to the speed of sound. While the present invention relies on time-of-flight calculations, it will be appreciated that the measurement of the horizontal pulse 32 provides self calibration to accommodate such changes. Where such changes are not an issue, the horizontal pulse 32 can be eliminated and replaced with user defined parameters.

The frequency of the ultrasound used for the interrogation will depend on the materials of interest. The selection of frequency will also depend on the size and geometry of the storage tank. The frequency selected is optimized for three parameters: transit time resolution, penetration, and beam divergence. Although the method is not limited to lower frequencies, one preferred system employs audible signals in the range of 15 kHz to 25 kHz that are combined with pulse compression signal processing methods to allow for extended penetration and high return (echo) signal.

Signal pulse compression methods can be applied to optimize the signal-to-noise and the time-of-flight resolution. For example, the transmitted signal may incorporate a predetermined range of frequencies, for example taking the form of a sine wave with continuously varying frequency conventionally referred to as a broadband frequency sweep. This approach uses a signal of wide bandwidth and long duration, a technique that is often used in radar applications, for example. The received signal is then cross-



correlated with the transmitted signal to determine the time-of-flight. The cross correlation of the received signal with the transmitted signal achieves a high signal to noise ratio and provides an accurate transmit signal arrival time.

An alternative pulse compression technique is the use of amplitude modulation to  
5 digitally encode a signal on a carrier frequency. In one application of this technique a distinctive binary phase shift modulated tag is digitally encoded in each pulse to uniquely identify its source transmitter. Such unique identification is particular useful in embodiments that utilize a multitude of transmitters and receivers. An analog, heterodyne receiver may be used to remove the high frequency carrier signal. This setup  
10 allows measurements to be made rapidly without resorting to extremely high speed digitization. The carrier signal may also be removed in software code using digital signal processing techniques directly on the received signals. As with other pulse compression techniques, the cross correlation of the received signal with the transmitted signal results in mostly signal contributions related to the encoded information and very little  
15 contributions from random, or white noise in the received signal, providing relatively high signal to noise and accuracy. Further details of pulse compression techniques useful in obtaining accurate and reliable information in the present invention can be found in Gan, T.H., Hutchins, D.A., Billson, D.R., and Schindel, D.W., "The use of broadband acoustic transducers and pulse-compression techniques for air-coupled ultrasonic  
20 imaging," *Ultrasonics* 39, 181-194 (2001); and Lam, F.K., and Hui, M.S., "An ultrasonic

pulse compression system for non-destructive testing using minimal-length sequences,”  
*Ultrasonics*, p.107-112 (1982).

## CLOSURE

5           While the invention has been illustrated and described in detail in the drawings  
and foregoing description, the same is to be considered as illustrative and not restrictive  
in character. Only certain embodiments have been shown and described, and all changes,  
equivalents, and modifications that come within the spirit of the invention described  
herein are desired to be protected. All publications, patents, and patent applications cited  
10   in this specification are herein incorporated by reference to the extent not inconsistent  
with the present disclosure as if each were specifically and individually indicated to be  
incorporated by reference and set forth in its entirety herein. Any experiments,  
experimental examples, or experimental results provided herein are intended to be  
illustrative of the present invention and should not be considered limiting or restrictive  
15   with regard to the invention scope. Further, any theory, mechanism of operation, proof,  
or finding stated herein is meant to further enhance understanding of the present  
invention and is not intended to limit the present invention in any way to such theory,  
mechanism of operation, proof, or finding. Thus, the specifics of this description and the  
attached drawings should not be interpreted to limit the scope of this invention to the  
20   specifics thereof. Rather, the scope of this invention should be evaluated with reference  
to the claims appended hereto. In reading the claims it is intended that when words such

as “a”, “an”, “at least one”, and “at least a portion” are used there is no intention to limit the claims to only one item unless specifically stated to the contrary in the claims.

Further, when the language “at least a portion” and/or “a portion” is used, the claims may include a portion and/or the entire items unless specifically stated to the contrary.

- 5 Likewise, where the term “input” or “output” is used in connection with reference to an electronic device, it should be understood to comprehend singular or plural and one or more signal channels as appropriate in the context.